A General Method for Dimensioning Antagonist, Artificial Muscles

Thomas Pomponio, Renaud Ronsse

***Abstract*—In this document, we develop a method to dimension antagonist artificial muscles to actuate a joint while modulating its stiffness through the biological principle of co-contraction. Our method relies on a linear model of the force-length characteristic of biological muscles. This model is then used to derive relationships between the activation levels of the artificial muscles and joint torque, equilibrium angle, and stiffness. In particular, we provide a graphical representation of these relationships that illustrates the principle of co-contraction and underlies our dimensioning method. Then, we illustrate our method with a numerical example by showing how to find the main characteristics of artificial muscles for a given operating point and stiffness range.**

I. Introduction

THE biological mechanism of co-contraction consists in simultaneously activating antagonist muscles to modulate the stiffness of a body joint. This mechanism is of interest for rehabilitation robots, since they would better adapt to the patient and absorb fast perturbations like spasms and tremors, in a way similar to a human therapist.

In this document, we propose a method to dimension artificial muscles to reproduce the biological principle of co-contraction, i.e. to reach an operating point defined by a torque and an angle while modulating the resulting joint stiffness. This method is independent of the technology of the artificial muscles. We first present models of artificial muscles and of actuated joint. Then, using these models, we derive the relationships between the activation levels of the muscles and joint torque, angle, and stiffness. Finally, we use a numerical example to show our framework can be used to find the main characteristics of the artificial muscles given torque and stiffness specifications.

II. Model of Artificial Muscles and Joint

A. Mechanical configuration

The artificial muscles and the joint are schematized in Fig. 1. The joint consists of a pulley, a shaft, and a link rotating about the shaft. The artificial muscles are attached to the link and the pulley. When the joint is in its neutral position, muscles are at mid-stroke. When it rotates, one muscle elongates and the other shortens. They apply forces on the link, resulting in a net torque τ about the shaft.

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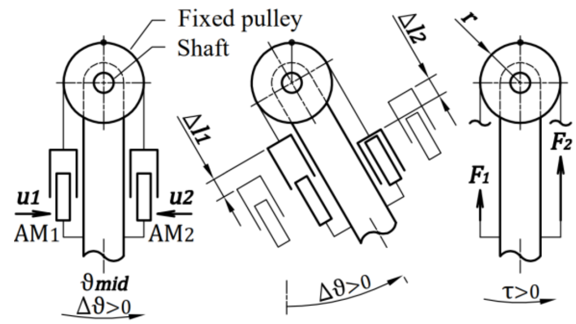

Fig. 1. Model of the joint with two antagonist artificial muscles.

B. Model of the artificial muscles

We assume that the force-length (F-l) characteristic of an artificial muscle can be captured by:

$$F(\Delta l, u) = \left(\frac{F_{max}+F_{min}}{2} + \frac{F_{max}-F_{min}}{2\,\Delta l_{max}}\Delta l\right)u \quad (1)$$

where F is the force produced by the artificial muscle, Δl and Δl_{max} are respectively the displacement and the maximum displacement w.r.t. mid-stroke, $u = [0,1]$ is the activation level, and F_{min} and F_{max} are the force produced by the muscle at end of stroke and full activation.

Equation (1) is represented in Fig. 2-A. It corresponds to the ascending region of the active F-l characteristic of biological sarcomeres or muscles (Fig. 2-B).

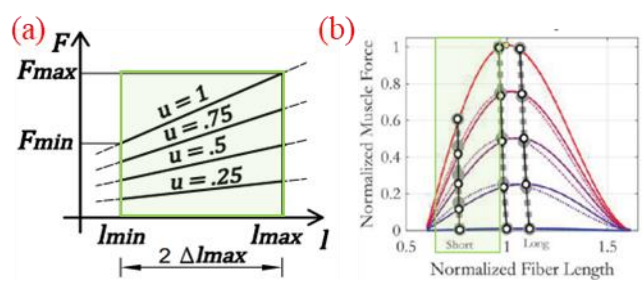

Fig. 2. (a) Model of the artificial muscles. (b) Model of biological muscles for activation levels 0.25, 0.50, 0.75 and 1 [1].

C. Joint dynamics

The net torque τ applied by the muscles on the link is given by:

$$\tau/r = F_2 - F_1 = a\,(u_2 - u_1) - b\,\Delta\theta\,(u_2 + u_1) \quad (2)$$

$$\text{with } a = \frac{(F_{max}+F_{min})}{2} \text{ and } b = \frac{F_{max}-F_{min}}{2\,\Delta\theta_{max}}$$

where r is the pulley radius, u_1 and u_2 are the activation levels of the artificial muscles, $\Delta\theta$ is the angle of the joint w.r.t. the neutral position and $\Delta\theta_{max}$ is the maximum angle of the joint. The length of the muscles in (1) has been replaced in (2) by the angles using $\Delta l_1 = -\Delta l_2 = r\,\Delta\theta$.

The joint stiffness R is the derivative of the torque with respect to the angle $\Delta\theta$, i.e.:

$$R = -b\,r\,(u_2 + u_1) \rightarrow b\,r\,(u_2 + u_1) \qquad (3)$$

III. Graphical Representation of Muscle Activation and Joint Stiffness

Let us assume that we want to reach a given operating point $(\tau, \Delta\theta)$ while being able to modulate the joint stiffness R within a desired range. From (2), the activations must satisfy the following equation:

$$u_2 = \frac{\tau}{r}\,\frac{1}{a - b\Delta\theta} + \frac{a + b\Delta\theta}{a - b\Delta\theta} u_1 \qquad (4)$$

This relationship is graphically represented by a segment AB, within a 1×1 square (Fig. 3). Using (3), stiffness can be represented in a second graph as a relationship between R and $(u_1 + u_2)$, i.e. tilted at 45° with respect to the original graph. When the point (u_1, u_2) moves along AB, the operating point $(\tau, \Delta\theta)$ is kept constant while the joint stiffness R varies within a minimum and a maximum value:

$$R_{min} = b\,r\,(u_{1A} + u_{2A}) \text{ and } R_{max} = b\,r\,(u_{1B} + u_{2B}) \quad (5)$$

This illustrates the principle of co-contraction, consisting in maintaining a posture and a torque while modulating antagonist muscle activations to change joint stiffness.

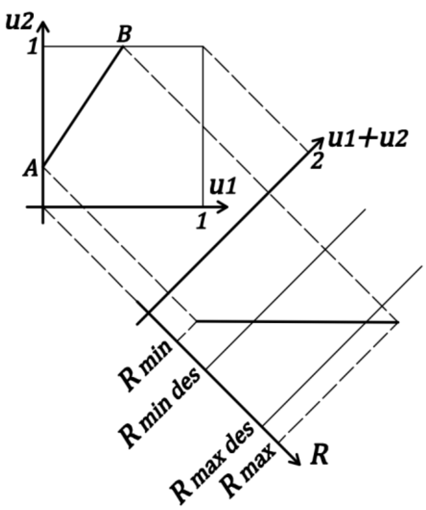

Fig. 3. Locus of muscle activations (u_1, u_2) for a given operating point $(\tau, \Delta\theta)$ and corresponding joint stiffness range $[R_{min}, R_{max}]$.

IV. Example of Dimensioning

In this section, we show how to find the main characteristics of a pair of artificial muscles, F_{min} and F_{max}, to reach a given operating point and a range of stiffnesses.

The selected operating point is (10 N, 0°) with desired stiffness that should vary within $R_{des} \in [31,102]$ Nm. This is based on values found in literature: 10 N is the maximum joint torque of the rehabilitation robot MIT-MANUS [2], and 31 and 102 Nm are the human shoulder stiffness during reaching movement in different force fields [3].

(4), (5) and Fig. 3 show that F_{min} and F_{max} define AB, which in turn defines the stiffness range. Therefore, using (4) and (5), we plot R_{min} and R_{max} as a function of F_{min} and F_{max} for the specified operating point (Fig. 4, top). Then, in the plots, we look for the lowest pair (F_{min}, F_{max}) for which the desired stiffness range is included in the possible range, i.e. $R_{min} < R_{\min des}$ and $R_{max} > R_{\max des}$. This pair is $F_{min} = 0$ N and $F_{max} = 1650$ N.

If the design torque is now 5 N and R_{des} is similar, then $F_{max} = 1580$ N (Fig. 4, bottom). The torque is reduced by 50% but F_{max} is reduced by 4% only. This illustrates the sensitivity of the required muscle characteristics as a function of the desired stiffness ranges.

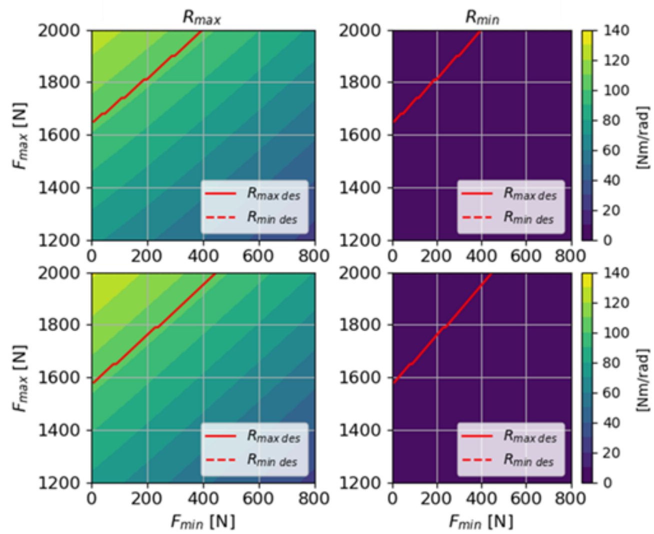

Fig. 4. R_{min} and R_{max} as a function of F_{min} and F_{max}. Top: operating point (10 N, 0°). Bottom: operating point (5 N, 0°). Plain red line: maximum desired stiffness (102 Nm). Dashed red line: minimum desired stiffness (31 Nm), not visible because $R_{min} < R_{\min des}$ for every F_{min} and F_{max}. ($\Delta\theta_{max} = 58.8°$ and $r = 0.07$ m.)

V. Conclusion

We proposed a model-based graphical approach for dimensioning a pair of antagonist artificial muscles leveraging the principle of co-contraction. The model assumes that the F-l characteristic of the muscles is linear. Although this assumption seems restrictive, it makes the model independent of the particular technology used to manufacture the muscles. The method can then be used during a predesign stage to estimate the required characteristics of artificial muscles, and then to select a suitable technology.

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